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Stable Plume Dispersion over an Isolated Hill Releases above the Dividing-Streamline Height

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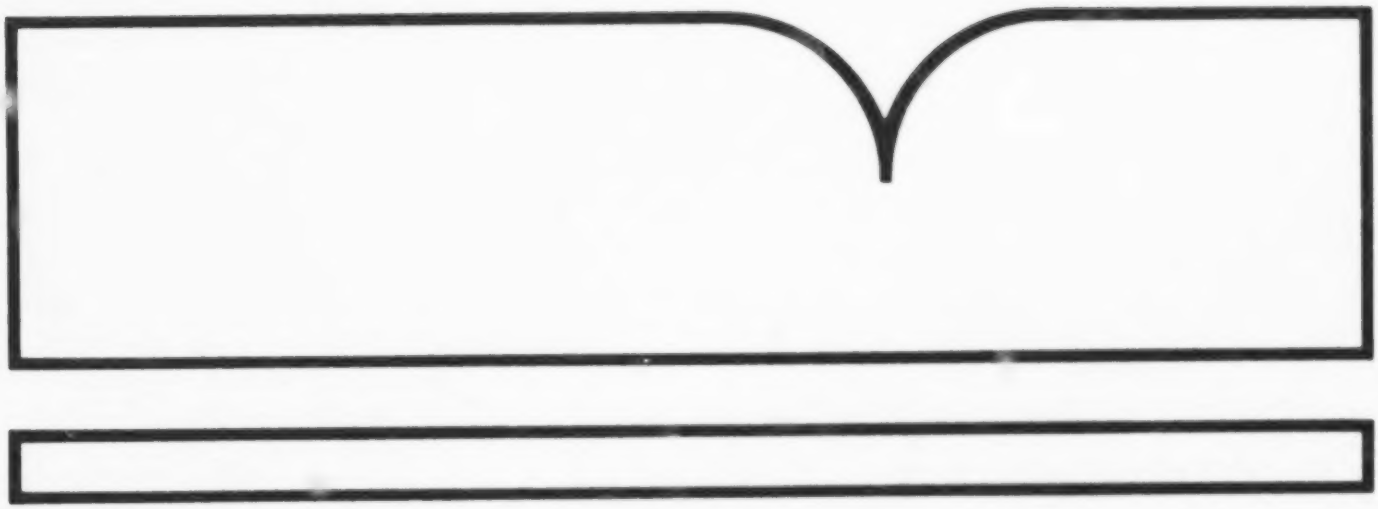

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by

William H. Snyder* and Robert E. Lawson, Jr.*
Atmospheric Sciences Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

*On assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

ATMOSPHERIC SCIENCES RESEARCH LABORATORY
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STABLE PLUME DISPERSION OVER AN ISOLATED HILL
Releases above the Dividing-Streamline Height

William H. Snyder† and Robert E. Lawson, Jr.†

Meteorology and Assessment Division
Atmospheric Sciences Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711 U.S.A.

ABSTRACT

A series of experiments was conducted in a stably stratified towing tank wherein the density gradient was linear and the dividing-streamline height H_D was half the hill height. Effluent was released at three elevations above H_D. Pairs of tows were made such that, in one tow, the hill (upside-down) was fully-immersed in the water and the towing speed was adjusted to provide a "natural" H_D surface. In the second tow of the pair, the hill was raised out of the water to the point where only the top half of the hill was immersed, thus, forcing a *flat* H_D surface. Concentration distributions were measured on the hill surface during each pair of tows and compared to ascertain effects of an assumed flat H_D surface as is used in some mathematical models. The results suggest that the assumption is a reasonable approximation to make, at least with regard to predicting the locations and values of maximum concentrations and areas of coverage on the windward side of the hill.

INTRODUCTION

The structure of strongly stratified flows over three-dimensional hills has been envisioned as composed of two layers: a lower layer of essentially horizontal flow wherein plumes from upwind sources impinge directly on the hill surface, and an upper layer wherein plumes may pass over the hill top. This basic concept was suggested by theoretical arguments of Drazin (1961) and Sheppard (1956), and demonstrated through various laboratory experiments (see Hunt & Snyder, 1980; Snyder & Hunt, 1984; and references therein). Complex terrain diffusion models utilizing this concept have been developed by Hunt et al (1979) and, more extensively, by Strimaitis et al (1985).

We are concerned here with the upper-layer flow. The basic assumption in this approach is that, in strongly stratified flows ($0<F<1$), a dividing-streamline height H_D exists wherein streamlines below H_D have insufficient kinetic energy to surmount the hill top and hence must pass

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†On assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

around the sides of the hill; streamlines above H_D may pass over the hill top. The simplest and easiest assumption to make in constructing a mathematical model (and the only one made to date) is that the dividing-streamline surface is perfectly flat, i.e., that the upper- and lower-layer flow regimes are separated by a horizontal plane. As discussed by Snyder & Hunt (1984), a plume released in the upper-layer flow (at H_S) upstream of a hill of height h may be treated like a release from a stack of height H_S-H_D upstream of a hill of height $h-H_D = Fh$, i.e., as if a ground plane were inserted at height H_D. The stratification above H_D, of course, has important influences on the diffusion as well as the vertical convergence and horizontal divergence of the streamlines, so that the flow structure over the hill of height Fh must be treated like that with F = 1.0, i.e., the Froude number of the flow over this smaller hill is unity.

The crucial question upon which we attempt to shed light is: how good is the assumption of a flat dividing-streamline surface? We know from laboratory studies that, even well within the lower layer, streamline trajectories are not contained within horizontal planes. Indeed, Hunt & Snyder (1980) and others used an extension of Drazin's (1961) theory to predict vertical displacements of streamlines in the lower layer. Also, the streamline originating at the dividing-streamline height far upstream on the flow centerline, by Sheppard's (1956) hypothesis, terminates on the surface at the top of the hill, again suggesting that the dividing-streamline surface cannot be flat. On the other hand, concentration measurements on hill surfaces (Snyder & Hunt, 1984) suggest that a flat surface approximation may yield reasonable estimates. From a practical viewpoint, mathematical models are vastly simplified if such an assumption yields reasonable estimates of surface concentrations. Hence, we attempt to answer the question, not from a detailed analysis of the shape of such a surface, but from the more practical comparison of surface concentration patterns.

A series of tows was conducted in the salt-water-stratified towing tank using, as the basic hill shape, a fourth-order polynomial hill as used by Hunt & Snyder (1980). Linear density gradients were established in the tank and the hill was towed at a speed U_∞ such that the Froude number F ($=U_\infty/Nh$, where N is the Brunt-Väisälä frequency) was 0.5. Effluent was released at heights of H_S = 0.6h, 0.7h and 0.8h, and the resulting hill-surface concentration patterns were measured. Since the density gradient was linear and F=0.5, the dividing-streamline height was also 0.5 ($H_D/h = 1-F$); since the effluent was released above H_D, the plumes did not impinge directly on the hill, but instead pollutants reached the hill surface by the combination of streamline displacement and diffusion. After that series was completed, a second series of tows was conducted wherein the entire model (hill, baseplate and stack, as a unit) was raised out of the water† to the point where the water surface was precisely at the dividing-streamline height, i.e., the water surface was at half the hill height. The model was towed at the same speed as in the full-immersion tows, so that the Froude number with this now half-height hill was unity, and all streamlines passed over the hill top. The flat water surface thus forced a flat dividing-streamline surface. The resulting surface concentration patterns were then compared with the corresponding

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†The model is routinely mounted upside down such that the baseplate is submerged a few millimeters below the water surface. In discussion of flow structure and plume behavior, however, we discuss the results as if the model were right-side up.

full-immersion tows to ascertain the effects of a flat dividing-streamline surface.

EXPERIMENTAL APPARATUS AND TECHNIQUES

Most of the details of the experimental apparatus and techniques were given by Hunt & Snyder (1980). The basic method of making concentration measurements was described by Snyder & Hunt (1984). Only a brief overview is given here. Further details may be obtained from Snyder & Lawson (1985).

A fourth-order polynomial hill ($z(r) = h/(1+(r/L)^4)$) of height 24.3cm and maximum slope of 45° was used in a stratified towing tank. The tank, 1.2m in depth, 2.4m in width and 25m in length, was stably stratified with layered mixtures of salt water. A neutrally buoyant dye mixture was emitted at 4 times the isokinetic rate from a bent-over "stack" of 0.635cm o.d. The stack exit was located 84.8cm (3.5h) upstream of the hill center. The non-isokinetic effluent release rate was used to obtain a realistic plume size and shape, i.e., a realistic simulation of a typical atmospheric situation. The maximum jet velocity at the hill center was estimated to be about 2cm/s relative to the hill, i.e., small compared with the towing speed. Characteristics of the plume in the absence of the hill were measured with horizontal and vertical rakes of sampling tubes.

The hill was covered with sharp-edged gravel of grain size in the range of 2 to 4mm. The rough surface eliminated a viscous sublayer on the hill surface and, hence, avoided problems of molecular diffusion through this viscous sublayer. One hundred sampling ports (2.4mm o.d. tubes) were fixed on the hill surface, distributed equally along 8 radial lines emanating from the hill center.

A vacuum system was used to draw samples through the surface ports into individual collection bottles (test tubes). The concentrations of dye in the collected samples were analyzed on a Brinkman Model PC-600 probe colorimeter. The output of the colorimeter, a voltage related to the opacity of the solution being tested, was fed to a PDP 11/44 minicomputer, where it was converted to concentration. The conversion utilized a calibration curve formed by recording the output voltage versus concentration for at least 12 "standards" which consisted of accurately known dilutions of the same dye used for the effluent source. The accuracy of the concentration-measurement system is estimated to be in the range of ±10 to 15%.

PRESENTATION AND DISCUSSION OF RESULTS

Plumes in the Absence of Hill

Vertical and horizontal concentration profiles were measured at the downstream position of the center of the hill (but in its absence) for each of three stack heights, 0.1h, 0.2h and 0.6h. For the two lowest stack heights, the baseplate was raised out of the water; for the highest stack height, it was submerged to the same depth as for the full-immersion tows with the hill (approximately 6mm). Concentrations have been normalized as $\chi = CU_\infty h^2/Q$, where C is the dye concentration, U_∞ is the towing speed, and Q is the volume flow rate of dye in the effluent. The calculated plume parameters are listed in Table I. The two higher-level plumes were essentially identical and very closely Gaussian in shape. (The parameter χ_{MXO} shown in Table I is the maximum concentration in the best-fit Gaussian distribution). The lower-level plume, however, had clearly diffused to the water surface; a

reflected-Gaussian profile, assuming an effective stack height of 0.09h, fitted the data quite well. The standard deviation of the vertical distribution σ_z (calculated assuming perfect reflection at the water surface), however, was 40% larger than those of the higher level plumes. The standard deviation of the lateral distribution σ_y of the lower level plume was also somewhat larger (10%) than that of the upper level plumes. The probable cause of this increased diffusion was a reduced stability near the water surface. Ideally, the density gradient would have been perfectly constant all the way to the water surface, so that the plume released at the lowest level (0.1h) in the half-immersion case would have been essentially identical in shape to that released at the upper level (0.6h) in the full-immersion case. However, as will be shown later, these differences in approaching plume shapes appeared to have little effect on the concentration distributions measured on the hill surface.

TABLE I. PLUME PARAMETERS AT POSITION OF HILL CENTER BUT IN ITS ABSENCE

H_s/h	Horizontal/ vertical	σ/h	χ_{MX}	χ_{MXO}
0.1	V	0.062[(a)]	21.1	22.2
0.1	H	0.105	22.4	24.0
0.2	V	0.044	25.8	28.7
0.2	H	0.097	23.6	27.2
0.6	V	0.044	23.4	25.3
0.6	H	0.094	21.6	25.1

(a) Calculated assuming perfect reflection at the water surface and an effective stack height of 0.09h.

Distributions on the Hill Surface

Fig. 1 shows side and top views of the plume surmounting the hill, in this case with the hill fully immersed and the effluent emitted at 0.6h. These photographs show the plume to be deformed to cover essentially the entire top surface of the hill, yet to be quite thin in the direction normal to the hill surface (the dotted line on the photographs marks half the hill height). Notice that, on the lee side, the plume sweeps to much lower elevations, so that we may expect to see substantial surface concentrations on the lee side below half the hill height. Just beyond the downwind base of the hill (not shown in the photographs), the flow separated from the surface and rose abruptly in a hydraulic jump (see Hunt & Snyder, 1980). Notice that, because of a vortex formed on the upwind side (it was intermittent in time and space), some plume material also appeared well below half the hill height both upwind and around the sides of the hill. Generally speaking, however, this did not lead to significant *surface* concentrations below half the hill height.

Similar views of the plume impacting on the hill surface in the half-immersion case are shown in Fig. 2. The most obvious difference between this case and the full-immersion case (Fig. 1) is that here the plume could not sweep down the lee side of the hill below half the hill height; it was constrained, of course, by the water surface (air-water interface). Similarly, the upwind vortex that transported plume material below half the hill height was absent in the half-immersion case.

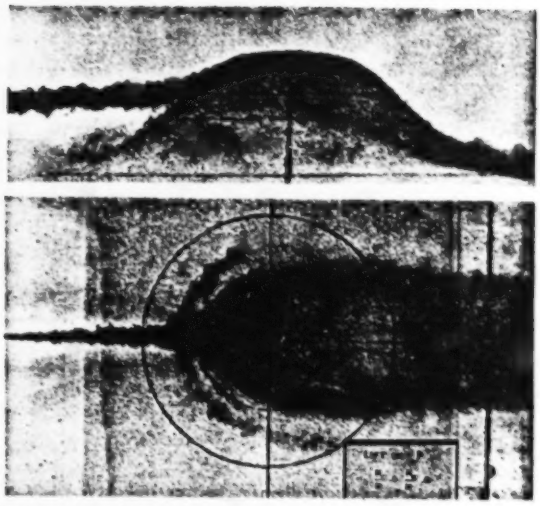

Fig. 1: Side and top views of plume released at 0.6h. Fully submerged.

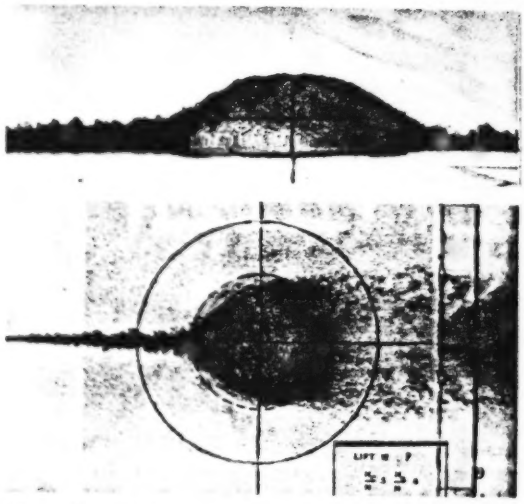

Fig. 2: Side and top views of plume released at 0.6h. Half submerged.

Fig. 3 shows the concentration distributions measured on the hill surface in both the half- and full-immersion cases. The most obvious difference between the two is the absence of lee-side concentrations below half the hill height in the half-immersion case. Of course, in this case, concentrations at positions below half the hill height were zero, because that portion of the hill was outside the water. In the full-immersion case, the plume diffused to some extent below half the hill height around the upwind side; also, as mentioned earlier, this plume "hugged" the hill surface as it was swept down the lee side to much lower elevation than the release height. In general terms, however, the shapes, values, and areas of coverage of the surface concentration distributions are quite similar above half the hill height.

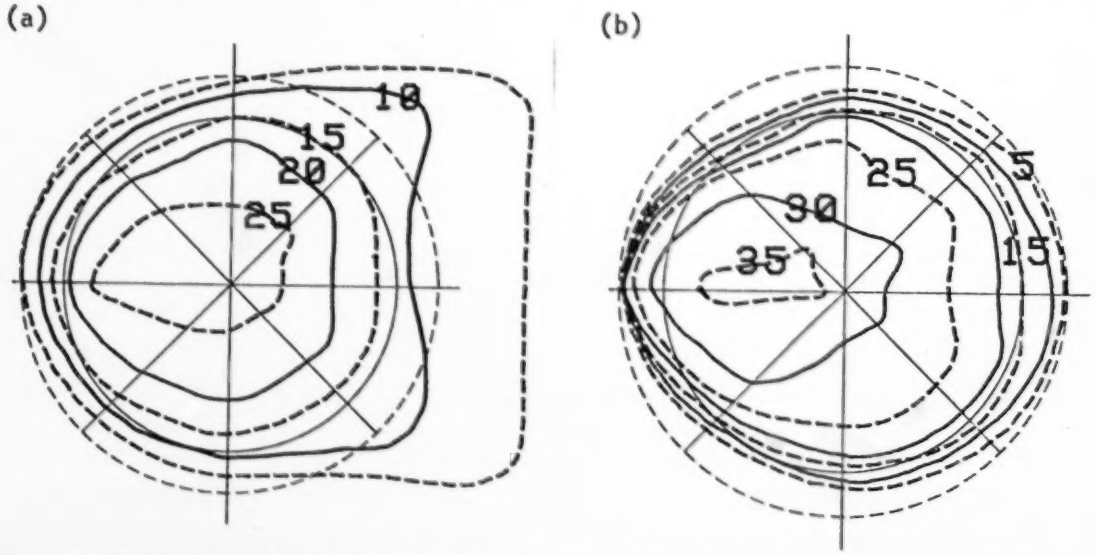

Fig. 3: Concentration distributions measured on hill surface. $H_s/h=0.6$. (a) fully submerged. (b) half submerged.

Fig. 4 presents a scatter diagram comparing, on a port-to-port basis, the surface concentrations measured in the half- and full-immersion cases. Measurements at points below half the hill height are not included here because, of course, in the half-immersion case, these ports were out of the water. Within the region of large concentrations, the two distributions compare quite favorably, the half-immersion case yielding concentrations approximately 10 to 20% larger than the full-immersion case. In the region of low concentration, quite large differences occur (worst case, a factor of 10). However, a close examination shows that in all cases where concentrations differed by more than a factor of 2, the port locations were very close to half the hill height, i.e., either at 0.505h or 0.59h.

Note that the maximum hill-surface concentration was in the range of 25 to 30, whereas the maximum in the plume in the absence of the hill was in the range of 20 to 25. This suggests that even though the plume shape was highly contorted through the streamline deformation process, the basic diffusion process was limited by the presence of the surface; this "reflection" at the hill surface resulted in a maximum surface concentration that was 20 to 25% larger than that observed at the center of the plume in the absence of the hill. However, as mentioned earlier, the accuracy of the concentration-measurement system was estimated to be in the range of ±10 to 15%, so that the above estimates of increased concentration should be taken with caution.

The concentration distributions resulting from sources elevated at 0.7h in the full- and half-immersion cases (not shown) were again quite similar. The contours on the windward side of the hill were roughly circular, but, in this case, somewhat more elongated in the streamwise direction. Again, of course, no concentrations were observed below half the hill height in the half-immersion case; in the full-immersion case, the plume "hugged" the lee side of the hill, but was spread less broadly in the crosswind direction and

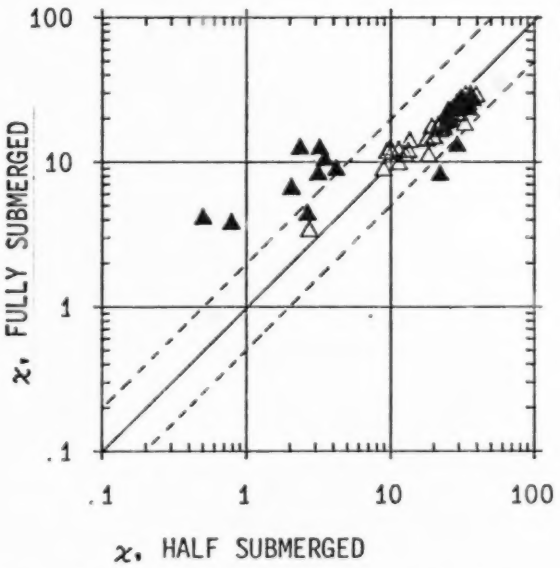

Fig. 4: Comparison of concentrations, half vs. fully submerged. $H_s/h=0.6$. Filled symbols: ports below 0.59h.

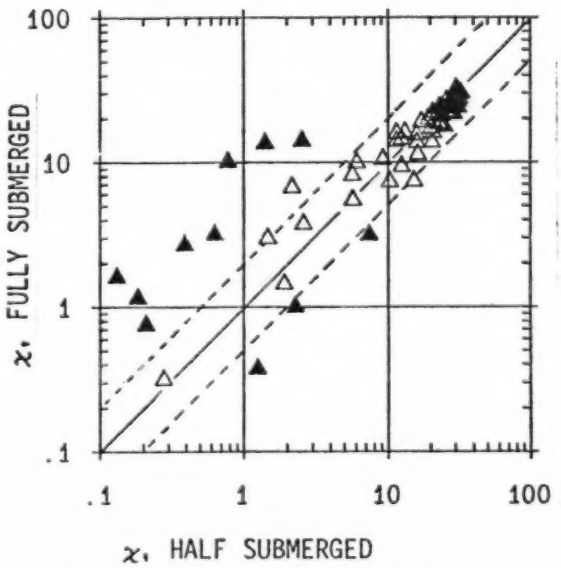

Fig. 5: Comparison of concentrations, half vs. fully submerged. $H_s/h=0.7$. Filled symbols: ports below 0.67h.

lifted off the surface into the hydraulic jump somewhat sooner. As was the case at a source height of 0.6h, the maximum concentration was about 10% larger in the half- than in the full-immersion case. The location of the maximum, however, moved from the windward side to the lee side of the hill.

A scatter diagram comparing these concentration distributions on a port-by-port basis for the half- and fully-submerged hills with a source height of 0.7h is shown in Fig. 5. The correspondence between the full- and half-depth immersions is not as good as was the case with a source height of 0.6h. For the large concentrations, the agreement is excellent, but for small concentrations, the scatter is quite large. Again, however, comparisons were poor only in the elevation range of 0.5h to 0.67h, i.e., near the water surface in the half-immersion case. In the half-depth case, concentrations were larger on the windward line of ports, apparently related to the wider vertical diffusion of the plume to the water surface, whereas concentrations elsewhere round the sides of the hill were considerably smaller than in the full-depth case.

Fig. 6 shows the concentration distributions resulting from sources elevated at 0.8h. In this case, the correspondence between the two distributions is not nearly as good as was the case at the lower stack heights. Whereas the locations of the maximum concentrations are approximately the same, the values in the full-immersion case are 55% larger and the area of plume contact on the hill surface is nearly quadrupled over the half-immersion case. Note that the location of the maximum concentration is well to the lee side of the hill and that the area of plume contact is much smaller than for the lower stack heights.

A scatter diagram comparing these two cases is presented in Fig. 7. The correspondence between the full- and half-depth immersion cases is clearly poor, with the half-depth immersion tow exhibiting surface concentrations that are generally less than half those from the full-depth tow. Both of these tows were repeated and the repeatability was found to be excellent, i.e., concentrations were generally within ±10% on a point by point comparison.

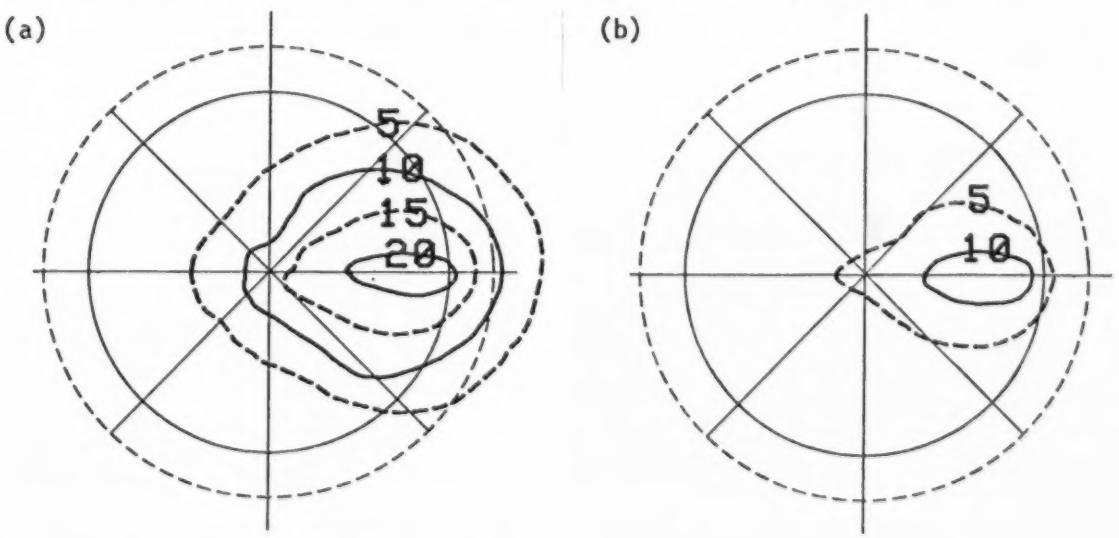

Fig. 6: Concentration distributions measured on hill surface. $H_s/h=0.8$. (a) fully submerged. (b) half submerged.

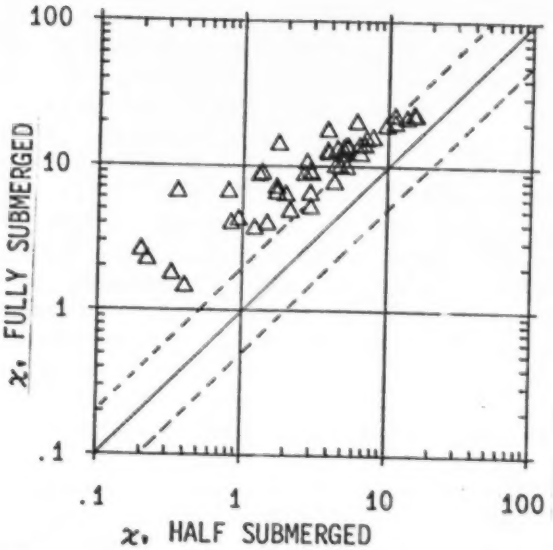

Fig. 7: Comparison of concentrations, half vs. fully submerged. $H_s/h=0.8$.

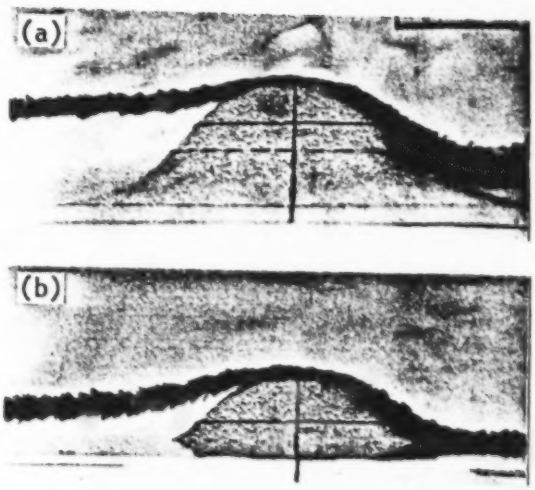

Fig. 8: Side views of plume released at 0.8h. (a) fully submerged, (b) half submerged.

The poor correspondence in this case may be partially understood by examining the side- and top-view photographs of the plumes as shown in Figs. 8 and 9. The top-views show that, in the half-depth tow, the plume was much narrower on the lee side of the hill. The side views show that, in the full-depth tow, the plume "hugged" the hill surface on the lee side to elevations considerably lower than half the hill height, then lifted off the surface and rose somewhat in elevation with the hydraulic jump at the downwind base of the hill (not seen in the photograph). This hydraulic jump was not present in the half-depth tow, and the plume remained essentially at the water surface. The presence of the hydraulic jump obviously affected the flow structure on the lee side of the hill and, therefore, the concentration distributions there.

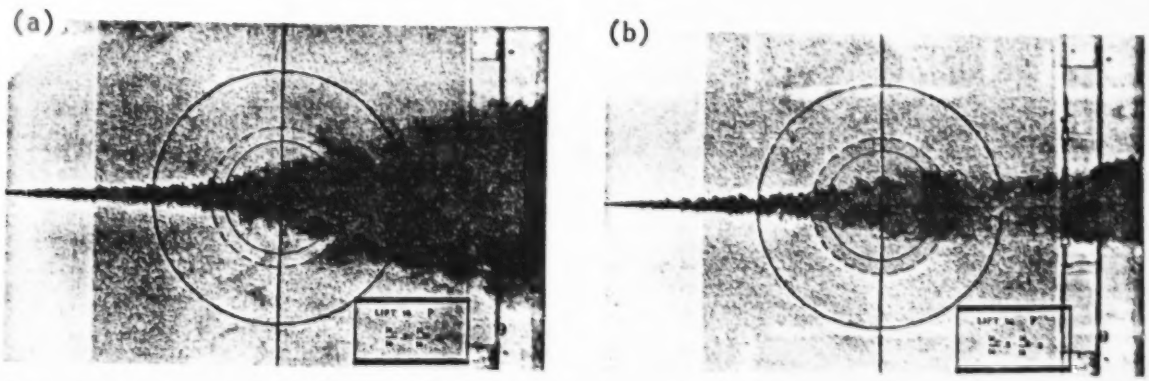

Fig. 9: Top views of plume released at 0.8h. (a) fully, (b) half submerged.

CONCLUSIONS

A series of tows was conducted in a stably stratified, salt-water towing tank wherein the density gradient was linear and the dividing-streamline height was half the hill height. Effluent was released at 0.1h, 0.2h and 0.3h above the dividing-streamline height, i.e., at elevations above the base of the hill of 0.6h, 0.7h and 0.8h. Pairs of tows were made such that, in one tow, the hill was fully immersed in the water and the towing speed was adjusted to provide a "natural" dividing-streamline surface (i,e., not flat) of half the hill height (far upstream). In the second tow of the pair, the hill was raised out of the water to the point where only the top half of the hill was immersed; this, in effect, forced a *flat* dividing-streamline surface (the water surface itself). In both tows of each pair, all other conditions were maintained identical, e.g., towing speed, effluent release height and flow rate, and density gradient. Concentration distributions were measured on the hill surface and in the absence of the hill. The distributions from each pair of tows were compared to ascertain the effects of an assumed flat dividing-streamline surface. Conclusions that may be drawn from this study are as follows:

1. Repeatability of concentration patterns from one tow to the next, under ostensibly identical conditions was generally within ±10%. The few points outside this range (but generally within a factor of two) were found to be on the edges of the plume where the concentrations were quite small and the turbulent fluctuations naturally result in this degree of variability.

2. At a stack height of 0.6h (0.1h above H_D), the maximum concentration occurred on the windward side of the hill; the plume was spread broadly to cover essentially the entire top half of the hill, but its thickness in the direction normal to the hill surface was small. Isoconcentration contours on the windward side were roughly circular. Comparison of the concentration patterns from the half- and full-immersion tows showed remarkable similarities over the top half of the hill. The locations of the maxima were essentially the same, although the value of the maxima were 10 to 20% larger for the half-immersion case. Regions of poor agreement included a thin band just above the half-hill height (where concentrations differed by, at most, a factor of about four) and, of course, everywhere below the half-hill height.

3. At a stack height of 0.7h (0.2h above H_D), the maximum surface concentration occurred just downwind of the hill center, with a value nearly the same as with the stack height of 0.6h. The plume was again spread broadly to cover most of the top half of the hill. Isoconcentration contours were again roughly circular on the windward side, but somewhat elongated in the flow direction. Comparison of the concentration patterns from the full- and half-depth tows again showed remarkable similarities and quite good agreement in the areas of higher concentration. Regions of poor agreement covered a broader band just above the half-hill height and, in that region, concentration values differed by as much as a factor of 8.

4. At a stack height of 0.8h (0.3h above H_D), the maximum concentration occurred well to the lee side of the hill; its value was substantially smaller than the maxima observed in the lower stack cases. Also in comparison with the lower stack cases, this plume was quite narrow and the area of coverage on the hill surface was quite small. Comparison of the concentration patterns from the full- and half-depth tows showed that, in areas of large concentrations, values of concentration differed by roughly factors of two.

In areas of low concentration, values differed by up to a factor of 10.

5. Observations of the flow structure revealed that a hydraulic jump occurred near the downwind base of the fully immersed hill, but was absent in the case of the half-immersed hill. This hydraulic jump appeared to have a rather minor effect on the streamline pattern near the surface on the lee side of the hill, but, as pointed out by Snyder & Hunt (1984), surface concentrations are extremely sensitive to the ratio of the plume thickness to the normal distance of the plume centerline from the hill surface when this ratio is near unity. Hence, even a seemingly minor change in the streamline patterns can have a major effect on the concentration patterns.

6. Maximum concentrations on the surface under the "worst" conditions were equal to or somewhat greater than those observed at the plume centerline in the absence of the hill.

7. These results suggest that the assumption of a flat dividing-streamline surface in a mathematical model is a reasonable approximation to make, at least with regard to predicting the locations and values of maximum concentrations (and areas of coverage) on the windward side of the hill. When the stack heights are relatively close to the dividing-streamline height, the lee-side concentrations would also be predicted reasonably well.

REFERENCES

Drazin, P.G., On the Steady Flow of a Fluid of Variable Density Past an Obstacle, *Tellus*, 13, 239-51, 1961.

Hunt, J.C.R., Puttock, J.S. & Snyder, W.H, Turbulent Diffusion from a Point Source in Stratified and Neutral Flows around a Three-Dimensional Hill: Pt. I: Diffusion Equation Analysis, *Atmos. Envir.*, 13, 1227-39, 1979.

Hunt, J.C.R. & Snyder, W.H., Experiments on Stably and Neutrally Stratified Flow over a Model Three-Dimensional Hill, *J. Fluid Mech.*, 96, 671-704, 1980.

Sheppard, P.A., Airflow over Mountains, *Quart. J. Roy. Meteorol. Soc.*, 82, 528-9, 1956.

Snyder, W.H. & Hunt, J.C.R., Turbulent Diffusion from a Point Source in Stratified and Neutral Flows around a Three-Dimensional Hill, Pt. II: Laboratory Measurements of Surface Concentrations, *Atmos. Envir.*, 18, 1969-2002, 1984.

Snyder, W.H. & Lawson, R.E. Jr., Stable Plume Dispersion over an Isolated Hill: Releases above the Dividing-Streamline Height, Appendix A: EPA Complex Terrain Model Development Fourth Milestone Report - 1984, Rpt. No. EPA/600/3-84/110, 233-68, Envir. Prot. Agcy., Res. Tri. Pk, NC, 1985.

Strimaitis, D.G., Lavery, T.F., Venkatram, A., DiCristofaro, D.C., Greene, B.R. & Egan, B.A., EPA Complex Terrain Model Development Fourth Milestone Report - 1984, Rpt. No. EPA-600/3-84-110, Envir. Prot. Agcy., Res. Tri. Pk., NC, 1985.